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Role of damage parameters in remaining life assessment of composites in Aircraft structures

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Abstract

Composites are being used in variety of applications ranging from aerospace-where the usage is profuse- to even microprocessors. Most of these composites are made of either different material with a matrix for binding or with fibers embedded in a composite matrix. The characterizations of material properties of composites are mostly experimental with analytical modelling used to simulate the system behaviour. In this study a typical composite- with characteristics as given in one of the earlier papers of the author is used to simulate the behaviour to study remaining life assessment-RLA- of the composites to enable one to design suitably. The damage is simulated in the form of hair-line cracks, introduced on the surface of the coupons used for testing. This investigation has been carried out on carbon fiber reinforced composite, manufactured by IPCL Boroda (India) with trade name INDCARF-30. The fibers are plain weave with 13-15 ends per inch in both wrap and weft direction. The epoxy resin used was Araldite LY-5052, hardened by Hardener HY-5052 (products of Ciba-Geigy India Ltd) with 100:38. Tests were conducted on undamaged and damaged specimens classified into vertical inclined and horizontal cracks and continuous and discontinuous loading was used to simulate normal and loading-and-unloading states in actual systems. Based on the experimental results, different values of E for the composite termed as Enc, Evc, Eic, Ehc, are obtained and used in analytical studies carried out using ANSYS to simulate stiffness decay. Using stiffness decay RLA was computed and curves are given to bring the influence of different parameters.

Key words: Composites; Life Time Assessment; Experimental Tests; Damage; Smart Structure

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1. INTRODUCTION

An aircraft and aerospace vehicles during its service life subjected to severe structural and aerodynamic loads, which may results from repeated landings and take-off, maneuvering, ground handling and environmental degradation such as stress corrosion. These loads can cause damage or weakening of the structure especially for an aging aircraft thereby affecting its load carrying capabilities and safe life. Strength and stiffness of composite materials [1] are two favourable properties that are used full extent in various structural applications under different kinds of loading. First the ‘long term’ behaviour that involves extended exposure of the component to applied condition that may include mechanical, thermal, chemical environment. Second , since the ‘end life’ is defined by the reduction of strength , the damage tolerance can be discussed in terms of strength , or more precisely in terms of reaming life after having some damage during in service. The composite behaviour generally reflects that of the matrix material, but with enhanced stiffness, strength and wear resistance [2,3]. These properties improve with increased volume fractions of reinforcement, however, the ductility decreases significantly, are known to have a significant influence on the macroscopic mechanical behaviour of CMCs by determining the stress states of the constituents (compressive or tensile stresses) in the composites and forming the damage to the composites in order to release themselves (matrix cracking, fiber-matrix deboning). Furthermore the distinguishing feature of unidirectional composites is that they have high strength and high modulus in the direction of the fiber-axis. This is more advantageous where the state of stress can be accurately determined and laminates can be fabricated with fibers having strength that can match the design needs. However, in applications where the state of stress may not be predictable or where the stresses are approximately equal in all major directions of loading, there is a need to develop composites that have approximately equal strength in all directions. In this context the bi-directional carbon fiber reinforced composites has attracted the attention of researchers and scientists to fulfill the analysis and design requirements under multi-directional loadings and also enable selection of material.

One of the essential requirements for this extensive usage is the need to understand the behaviour of these materials under different loading and environmental conditions. Any uncertainty in this regard will result in improper utilization of the material properties and will result in smaller or larger margins of safety in design. The present day loadings and environments, to which these composites are subjected to, are so varied and complex that it necessitates a complete understanding of the material response over the entire range of the load. Residual stresses could be detrimental to the integrity of the structure because the total stress, that is the stress resulting from the applied load added to the residual stress, may be higher than for in design. Clearly, a reliable method for measuring such stresses would be of this article the remaining life assessment of the carbon fiber composite used in the aerospace application with induced crack in different direction are studied. In an earlier paper by Dash and Singh [2], some basic characteristics of the composite were presented mainly with special reference to shear behaviour and later in other papers [3,4,5,6], the authors have reported on different aspects of system response using this type of composite. Now in this study, an extension into damage and its effect on response are presented using numerical approaches.

Nomenclature

NNC - New no crack	NVC – New vertical crack	NIC - New inclined crack
NHC -New horizontal crack	BC’s -Boundary Conditions	LC’S -Loading Conditions
CMC -Carbon Matrix Composites	THK –Thickness	

2. EXPERIMENTAL METHODOLOGY

2.1. Materials and Test Details

This investigation has been carried out on carbon fiber reinforced composite [2,3], manufactured by IPCL Baroda (India) with trade name INDCARF-30. The fibers are plain weave with 13-15 ends per inch in both wrap and weft direction. The properties of weaved carbon fiber fabric are mentioned in Table 1.The epoxy resin used was Araldite LY-5052, hardened by Hardener HY-5052 (products of Ciba-Geigy India Ltd) with 100:38. The composite plates were fabricated in the vacuum bag technique and cured at room temperature for 24h and post – cured at 100°c for 2h. The laminates made with eight layer of fabric have a nominal thickness of 1.68 mm corresponding to a fiber volume fraction of 55 %(+ 1). The basic properties of the fabricated carbon /epoxy material are presented in Table 2. In this section, the specimens preparation and the environmental selection were made initially followed by the different induced crack in different orientation and test were conducted on UTM (Fig.1) tensile test to predict the remaining life assessment of the composite with damage and virgin specimens.

2.2. Specimens Preparation

The specimens were prepared from the fabricated carbon reinforced composite plate. The virgin specimens and the specimens with induced cracks in different orientation i.e. horizontal, vertical and inclined are as shown in figure 2. The length and depth of the crack was fixed of 10 mm and 0.8 mm respectively in cracked specimens of different orientation. The specimens were tested in four different states undamaged, damaged with vertical crack, damaged with inclined crack and lastly damaged with horizontal crack. Based on test results, characteristic properties like young's modulus, stress and strain at different loads were obtained which will be used in analytical model. Testing methodology and tested specimens after failure are shown in Fig.1

a) b)

Fig.1 Testing and failure of specimens. (a) Testing set-up b) Failed specimens.

3. ANALYTICAL METHOD

Finite element method of analysis using industry tested software ANSYS was used to do detailed analytical study and here both linear and nonlinear analysis accounting material changes are done to get an idea of the influence of type and spread of damage. Damage due to cracks is reflected in choosing reduced material properties at damaged zones. Material nonlinear analysis is performed using elastic-perfectly plastic concept with varying strain hardening parameters. Finite element model with actual domain and the mesh used with boundary conditions are shown in Fig.2.

(a) (b) (c)

Fig.2 Analytical model (a) Domain for analysis b) Sub-regions of model c) Chosen mesh for analysis

4. RESULTS AND DISCUSSION

The results of analytical study are presented mainly to bring out the influence of type of damage, spread of damage and the non-linearity due to material yielding. Correspondingly the stiffness of all models is taken to assess the decay which will play a role in remaining life assessment-RLA- of the composite using undamaged state as basis.

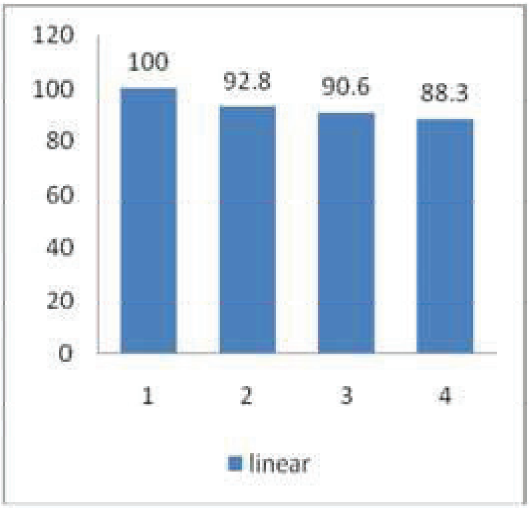
In this study, different cases with the small region of specimen near the central symmetric layer affected with the crack/damage, and the remaining region in a virgin state are studied. FE analysis of the region of interest of specimen is meshed into layers and elements as fine as possible. Convergence study revealed the choice of the model chosen for converging results. Analysis is carried out by considering that the crack is propagating either element by element or layer by layer. Separate cases of the analysis were carried out with different types of initiation followed by different types of spread both from initiation and spread points of view so that damage effects in terms of cracks could be quantified as a parameter in terms of stiffness for remaining life studies. Further nonlinear effects are taken into account by assuming an elastic-plastic stress-strain curve with values of hardening parameters, ranging from .0025 to .01 in the inelastic state. The idea behind this is to assess the decay of stiffness with different kinds of damage like

- Vertical crack progressing vertically or inclined or horizontally
- Inclined crack progressing to vertical or inclined or horizontal and
- Horizontal crack progressing to vertical or inclined or horizontal

Using NNC for no crack, NVC, NIC and NHC for vertical, inclined and horizontal crack initiation, VV VI and VH for propagation into two layers and VVV, VII and VHH for three layers, detailed analysis in elastic and inelastic ranges were carried out and using these results stiffness evaluation is done to get an idea of the change with respect to crack initiation and crack spread. Also the crack location whether at end or centre of domain is taken as a parameter for remaining life estimation. These are given in separate sections for type of crack initiation, manner of spread and whether material in elastic or inelastic region of response.

4.1. Influence of type of damage/rack initiation

Under static elastic behaviour crack initiation vertically-parallel to the load- reduces the stiffness only marginally whereas inclined and horizontal cracks stiffness decay is pronounced. Histogram on the decay of stiffness is shown in Fig.3. But when the damage spreads either in an inclined or horizontal way, stiffness decay gets accentuated as shown in Fig.4. As many options are there for the spread like vertical followed by vertical or inclined or horizontal. Fig.4 shows for the critical ones only.



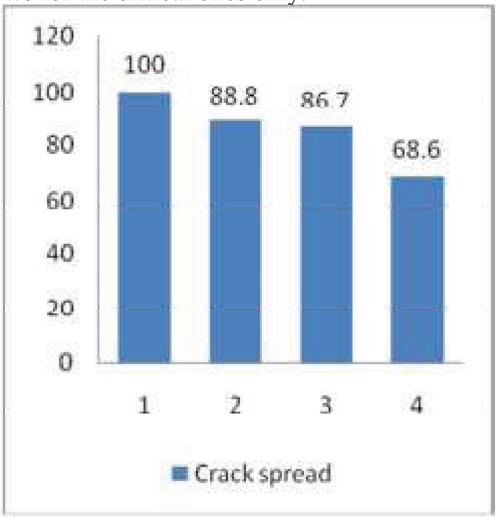


Fig.3 Stiffness decay for initiation

Fig.4 Stiffness decay with initiation and spread

While crack initiation normal to loads, brings down maximum effect on stiffness, as high as 11.7%, spread of crack after initiation into horizontal of any type of initiation shows a different behaviour. For example if a vertical crack spreads horizontally, its effect on stiffness reduction is high as compared to vertical or inclined. Spread of horizontal crack in horizontal direction has a significant effect bringing the stiffness down from 11.7% to 31.4%.

4.2. Influence of inelastic effects on rack initiation and spread

Since cracking creates inelastic effects near the damaged portions, material nonlinear analysis was performed using different hardening parameters ranging from .005 to .01 and Fig.5 gives details of these results for vertical, inclined and horizontal crack initiation cases. It may be seen that the decrease is pronounced for strain hardening of crack is developing in the same direction as load.

Further depending on how the crack spreads with nonlinear effects needs to be looked and since number of cases arise, only critical curves are given in Fig.6. Here curve a) gives load-deformation characteristics if the initiation and spread are vertical, that is parallel to load direction. It may be seen that the curves follow classic elastic plastic behaviour, with gradual reduction as the hardening parameter increases. But when the crack occurs normal to load and spreads in the same direction the behaviour tends to become more curvilinear as may be seen in Fg. 6(b). The spread also is wider than vertical damage.

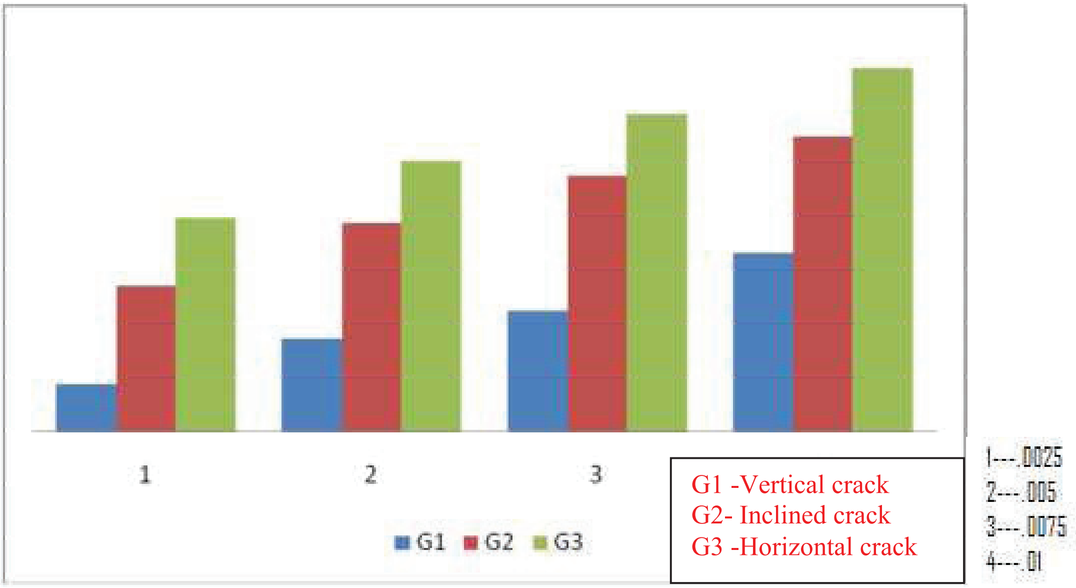


Fig.5 Effect of nonlinearity from .0025 to .01 for different type of crack initiation

Further depending on how the crack spreads with nonlinear effects needs to be looked and since number of cases arise, only critical curves are given in Fig.6. Here curve a) gives load-deformation characteristics if the initiation and spread are vertical, that is parallel to load direction. It may be seen that the curves follow classic elastic plastic behaviour, with gradual reduction as the hardening parameter increases. But when the crack occurs normal to load and spreads in the same direction the behaviour tends to become more curvilinear as may be seen in Fg. 6(b). The spread also is wider than vertical damage.

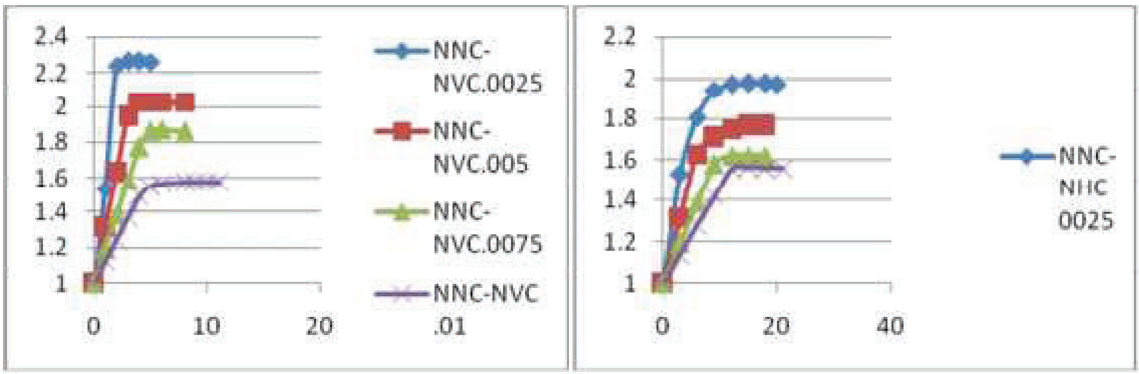


Fig.6 Effect of nonlinearity on load-deformation (a) Vertical crack b) Horizontal crack

Because of the effect of material decay, stiffness decay in elastic and inelastic cases also changes and this is shown as comparison with elastic case for different crack initiation in Fig.7. One can see clearly the inelastic effects for vertical cracking shows more spread than either inclined or horizontal crack initiation.

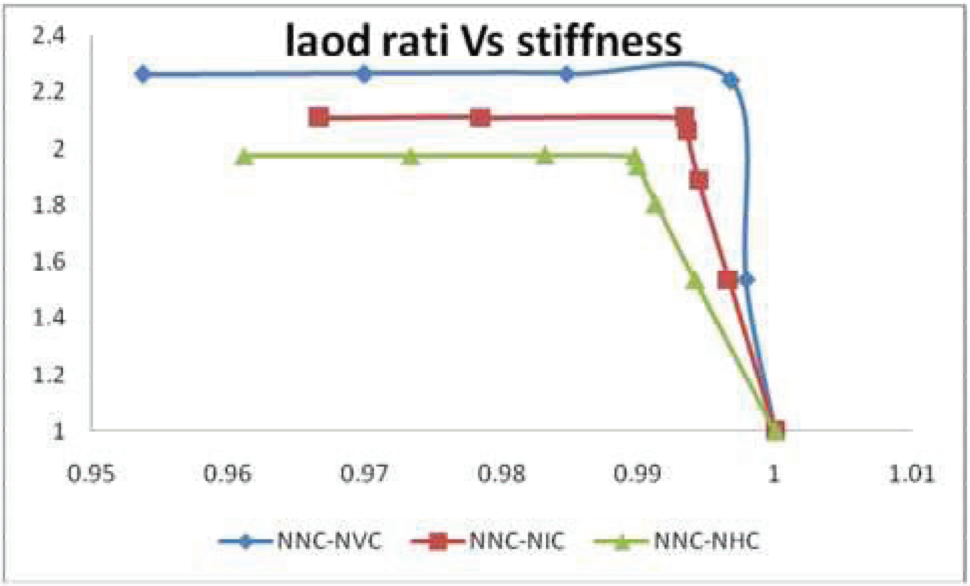


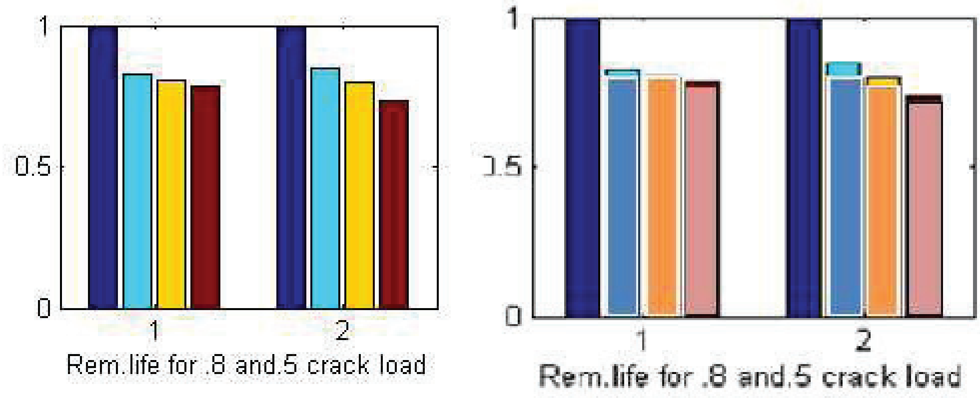
Fig.7 Stiffness decay with nonlinear effects

4.3. Remaining life assessment-RLA

The background studies done so far are used for predicting or assessing remaining life for the composite once it is cracked and damaged. For assessing remaining life, two essential parameters with respect to loadings are time- dependence and time-independence[7,8,9]. If a damage occurs at a certain level of the design load and later if the system has to perform for carrying the remaining load, it is necessary to know whether its stiffness[10,11,12] is sufficient or not. But if the loading is a cyclic load after the crack is initiated, fatigue response needs to seen. Using the values of displacements at the end and centre stiffness of the specimen can be evaluated to arrive at the decay which will influence remaining life of the component or system. The decay in stiffness for the initiation of cracks at centre is shown in Fig.6 as a factor with uncracked specimen. If the uncracked specimen is designed for a stiffness of k, then a vertical crack initiated at the centre of the specimen will bring down the value by 7 % for vertical, 27% for inclined and 51% for horizontal crack initiation showing clearly the effect on remaining life.

If a component is loaded to 80% of its design load and if crack gets initiated, the remaining life can be found as the ratio of damaged and undamaged values. This is shown for two cases with crack occurring at 50% and 80% of the load. The reduction in remaining life is clearly seen. The % reduction can go from 8% to 27% depending on initiation. Since location of crack/damage is also important, two extreme cases were considered one at edge and another at centre and the effect of damage is shown in Fig.9. Crack or damage can get initiated either at edges or at centre depending on loading and composite properties.

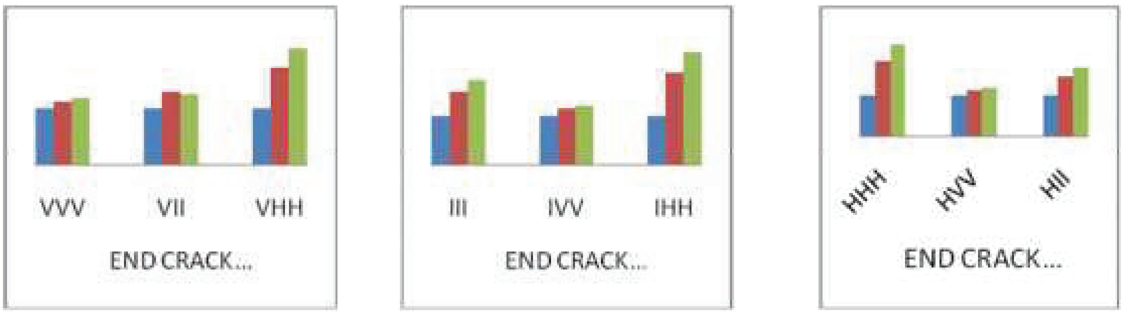
Consequently the response and remaining life get affected ad this is directly related to loss of stiffness. Again crack initiation and spread play a role and this is shown for two extreme cases, edge cracking and central cracking. With notation for V,I,H for type and VII or HVV for spread the histograms show the variation loss of stiffness.



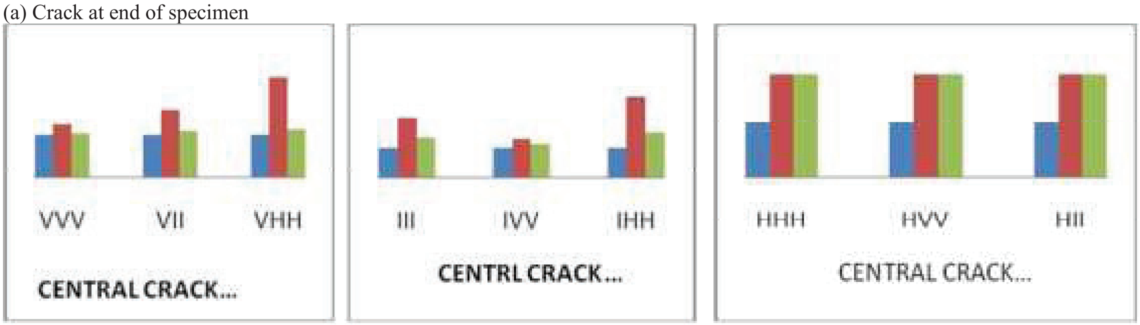
(a) Elastic behaviour (b) Inelastic behaviour

Fig. 8 Stiffness decay, cracking load and remaining life

Consequently the response and remaining life get affected ad this is directly related to loss of stiffness. Again crack initiation and spread play a role and this is shown for two extreme cases, edge cracking and central cracking. With notation for V,I,H for type and VII or HVV for spread the histograms show the variation loss of stiffness.



(a) Crack at end of specimen



(b) Crack at centre of specimen

Fig.9 Effect of crack location on stiffness

Now with loss in stiffness for different parameters, remaining life assessment-RLA- can be found and is shown in Fig.10. Here the variation is linear as the calculation of remaining life is done on linear variation in stress with type of loading and occurrence of crack

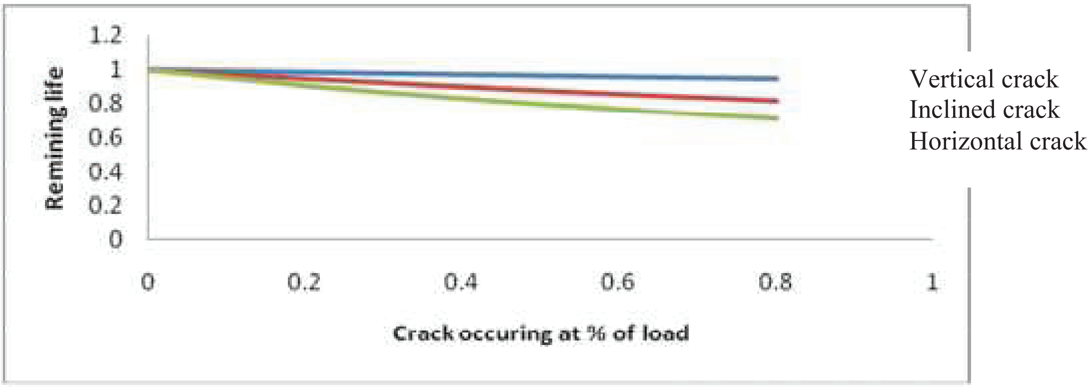


Fig.10 Effect of crack/damage on remaining life

5. CONCLUSIONS

From the experiment results conducted on the UTM under controlled environmental conditions and FEA results, it may be seen that the horizontal induced crack –normal to loads-is the dominating factor above all the other induced crack types in the specimens. And stiffness being the highest in the virgin state of specimens gets considerably affected by type and spread of damage and inelastic material behaviour. Hence while predicting the remaining life of the composites during service under different loading and environmental conditions if the crack is of horizontal nature that is in perpendicular to the fiber loading directions can lead to the catastrophic failure in the aerospace vehicles. The second we have seen from the bar chart that inclined induced crack is next dominating factor in predicting the remaining life assessment of the composites. Hence we can conclude that the remaining life of damaged carbon fiber bi-directional composite specimens will be less if the crack is perpendicular to the loading direction. It is proposed to use these stiffness values for modelling remaining life through 1-D and 2-D FEM.

6. Acknowledgements

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References

[1] Sanford,G.E. et eal (2009) "Failure testing of large composite aerospace structures"www.csa.com

[2] P.K. Dash, D. Singh,(2010) Shear Characterization Of Woven Carbon /Epoxy Composite Under Various Adverse Environments (International journal 2010 Blackwell Publishing Ltd/strain(2010) doi: 10.IIII/j.1475-1305.2010.00736.x

[3] Dalbir Singh et eal Studies on Crack configuration and Initiation in composites for remaining life assessment .2011 IEEE Aerospace Conference AIAA, Technical Co- Sponsor Mrch5-12, 2011 Big Sky,Montana.978-4244-7351-9/11/$26.00©2011,IEEAC paper#1751.

[4] Dalbir Singh, P.K.Dash (2010) Remaining Life Assessment of Composites with Damage“ ICIWSE - 2010 International conference On INNOVATIVE WORLD OF STRUCTURAL ENGINEERING September 17-19, 2010, Aurangabad, India”.

[5] Dalbir singh ,P.K.Dash,A.Rajaman (2010) Crack Initiation and its Effect on Life Assessment of Composites ,24th National Convention of Aerospace Engineers and National seminar on “NEW VISTAS IN AVIATION AND AEROSPACE “ Nov 13, 14,Institution of Engineers (India) Rajasthan.

[6] Dalbir Singh et eal., “Study of Composites with Damage for Remaining Life Assessment”, THE SEVENTH STRUCTURAL ENGINEERING CONVENTION 08 - 10 December, 2010 Department of Civil and Structural Engineering, Annamalai University.

[7] Chevalier, J., C. Olagnon, G. Fantozzi, (1999) “Crack propagation and fatigue in zirconia – based composite”Elsevier Science Ltd.Composites: Part A 30525-530

[8] Ehart, R.J.,S.E.Stanzl-Tschegg,E.K.Tschegg, (1998) “ Crack face intrection and mixed mode fracture of wood composite during III loading” .Engineering fracture Mechanics 61 253-278.

[9] Taoling Yang, Yunbo Liu, J. Wang,(2003) “A Study of the Propagation of an Embedded Crack in a Composite Laminate of Finite Thickness”, Composite Structures 59 473_479.

[10] Nidal Alif, Leif A. Carlsson, Louis Boogh,(1998), “The effect of weave pattern and crack propagation direction on mode I delamination resistance of woven glass and carbon composites”, 29B 603-611.

[11] Y. C.Her, P. C. Wang , J. M. Yang,(1998) “Fatigue crack initiation and multiplication of unnotched titanium matrix composites”, Acta moter. Vol. 46, No. 18, pp. 6645-6659.

[12] S.Gungor,(2002)”Residual stress measurements in fibre reinforced titanium alloy composites”, Acta Materialia 50 2053_2073.

Table 1. The Properties of Bi-directional weaved carbon fibre fabric

Property	Magnitude
Weight/sq. metre of the fabric	200 gms
Thickness	0.2 mm
Fibre count	3 K carbon
Yarn denier	-
Wrap	54
Weft	52
Weave	Plain weave

Table 2. Mechanical properties of Bi-directional carbon/epoxy composite

Mechanical properties	Tensile strength (MPa)	Young’s modulus(GPa)	Flexural strength (MPa)	Flexural modulus(GPa)
	583.32	37.069	483.23	30.064

Table 3. Results with 4 layers in the area of interest

No. of layers of Elements with modified E values	Crack Orientation	Young's Modulus, E(N/mm2)	Load (N)	Deflection (mm) EXPERIMENT	EXPERIMENTAL Stiffness	Deflection (mm) FEM	FEM Stiffness	Stiffness Decay Experimental (%)	Stiffness Decay FEM (%)
N/A	NNC	7.60E+04	18300	17.45	1.0487	14.075	1.00	0	0
	NVC	7.10E+04	17500	17.993	0.9726	14.135	1.238062	7.2574	0.1026
1	NIC	6.10E+04	16500	17.347	0.9511	14.287	1.154896	9.3007	0.7632
	NHC	5.23E+04	12000	12.906	0.9298	14.473	0.82913	11.3387	0.1791
	NVC	7.10E+04	17500	17.993	0.9726	14.195	1.232828	7.2574	0.5249
2	NIC	6.10E+04	16500	17.347	0.9511	14.499	1.13801	9.3000	2.2065
	NHC	5.23E+04	12000	12.906	0.9298	14.871	0.80694	11.338	2.7458
	NVC	7.10E+04	17500	17.993	0.9726	14.255	1.227639	7.2574	0.9436
3	NIC	6.10E+04	16500	17.347	0.9511	14.712	1.121533	9.3007	3.6084
	NHC	5.23E+04	12000	12.906	0.9298	15.27	0.785855	11.3387	5.1746
	NVC	7.10E+04	17500	17.993	0.9726	14.315	1.222494	7.2574	1.3588
4	NIC	6.10E+04	16500	17.347	0.9511	14.924	1.105602	9.3007	4.9639
	NHC	5.23E+04	12000	12.906	0.9298	15.668	0.765892	11.3387	7.4938